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ASSESSMENT OF RADAR PARAMETERS FOR HYDROMETEOR SCATTER MEASUREMENT USING THE ALCOR AND TRADEX RADARS AT KWAJALEIN

David W. Blood
Robert K. Crane

Environmental Research & Technology, Inc.
696 Virginia Road
Concord, Massachusetts 01742

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report documents the scattering relationships and radar parameters which enter into the measurement of effective radar reflectivity, $Z_e$, obtained from the ALCOR (C-band) and TRADEX (S-band) radars operated at Kwajalein Atoll for hydrometeor scatter investigations. An assessment is given of the calibration procedures used for the radars including assumptions, corrections, and uncertainties associated with the parameters used in the measurements. The current best estimate radar constants for ice and water used for data processing are documented for users of the data together with an editing criteria for rain

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20. (continued)

data, based upon the principal-to-opposite polarization received power ratios. The study program for AFGL is supported under Contract F19628-79-C-0007 for assessing the errors associated with the measurement of reentry environmental conditions for U.S. Air Force programs at the Kwajalein Missile Range.

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## 1. INTRODUCTION

Radars, operated at the Kwajalein Missile Range (KMR) at Kwajalein Atoll, Marshall Islands on the island of Roi-Namur, collect weather data on hydrometeor scatter before and after reentry missions of importance to military programs. Two of the radars, ALCOR and TRADEX, part of the Kiernan Reentry Measurement Site (KREMS) facility operated by the Army Kwajalein Missile Range Directorate, BMD Systems Command under the direction of MIT Lincoln Laboratory, are used for the collection of the data on clouds and precipitation. These investigations, conducted by the Air Force Geophysics Laboratory for diagnostic measurements and studies, are in support of U.S. Air Force SAMSO/ABRES programs for the assessment of the severity of projected and actual environmental conditions. The ALCOR radar operates at C-band (5664 GHz) and has been used for weather scanning and backscatter data collection. The 12-meter antenna is housed in a radome. The TRADEX radar has a 26 m reflector (no radome) and operates at S-band (2951 GHz) for the same purposes on this type of data collection. The emphasis in this report is on the documentation and definition of the parameters, assumptions and constants used in the backscatter mode when the radars are operated and data are digitally recorded for analysis and interpretation in terms of hydrometeor scatter.

The use of the KREMS radars for weather data collection has been previously documented (Lewis, 1978) with emphasis on overall weather measurement capabilities and on a particular software program called "MOIST" also developed for AFGL for use at sites in the real time assessment of moisture content and weather severity conditions in the troposphere. Recently, however, the radar parameters have been scrutinized again with regard to definitions and an assessment of errors and bias terms involved in calibrating the radars and processing the data. This report serves as a documentation of the updated results and should prove useful to those involved in the quantitative analysis of the backscatter data.

As a result of this study, the scattering relationships, Section 2, have been reviewed with a special emphasis on signal processing corrections and radar calibration uncertainties in Section 3. The signal processing effects which potentially can produce bias in the measurements are incorporated into the formulation as correction terms. The radar calibration uncertainties must be considered an estimate of the experimental error of measurement with random occurrences. These sources of measurement error are summarized in Table 1 in terms of RMS ($1\sigma$) uncertainty in decibels upon the measurement of backscattered radar cross section and effective radar reflectivity (directly proportional). Finally, a section on data interpretation is included (Section 4) to assist in the selection of hydrometer scatter due to rain using the dual polarization capability of the KREMS radars.

## TABLE 1

SUMMARY OF SOURCES OF MEASUREMENT UNCERTAINTY IN KREMS RADAR HYDROMETEOR BACKSCATTER DATA USING THE RADAR EQUATION AND IN RADAR CALIBRATION[1.]

| Source and Affected Term[2.] | Estimated Maximum Uncertainty (dB) ALCOR | Estimated Maximum Uncertainty (dB) TRADEX |
|---|---|---|
| Quantization, $P_{out}$ | 0.25 | 0.5 |
| Attenuators, A | 0.05 | 0.05 |
| Range, $R^4$ | 0.1 | 0.1 |
| Transmitted Power, $P_t$ | 0.1 | 0.1 |
| Beamwidths, $\Theta$ & $\phi$ | 0.5 | 0.5 |
| Calibration Constant, $K_{RCS}$ | 0.6 | 0.6 |
| Receiver/Matched Filter Stability (short term), $P_R$ | 0.5 | 0.5 |
| Propagation Effects and System Loss Differences (calibration-to-test)[3.], L | 0.5 | 0.3 |
| Total Estimated Maximum Uncertainty | ±2.6 dB | ±2.7 dB |
| Estimated RMS ($1\sigma$) Uncertainty | ±1.0 dB | ±1.0 dB |

1. see section 3.2

2. see equations (15) and (16) and associated relationships

3. omitted from treatment are possible polarization mis-match losses, m, and radome attenuation changes both assumed here to have zero dB uncertainty throughout a hydrometeor measurement

## 2. EFFECTIVE REFLECTIVITY FOR DISTRIBUTED HYDROMETEOR SCATTER

### 2.1 Backscatter from Rain

For backscatter from rain drops, the radar reflectivity or scattering cross section per unit volume, $\beta$, is the volume summation of the reflectivities, $\beta_i$, from individual scatterers:

$$\beta = \frac{1}{V} \sum_{vol} \sigma_i = \frac{\text{total radar scattering cross section}}{\text{volume of scattering}}$$

For radar wavelengths large compared to the drop size such that Rayleigh scattering holds, i.e. for small spherical water droplets and radar frequencies below 7 GHz; the particle backscatter cross section is:

$$\sigma_i = \frac{\pi^5}{\lambda^4} |K|^2 D_i^6 \quad , \quad |K| = \left|\frac{\varepsilon-1}{\varepsilon+2}\right| \tag{1}$$

where $\varepsilon$ is the dielectric constant for the drop;

$\lambda$ is the radar wavelength; and

$D_i$ is the diameter of the drop.

For volumetric scatter, the total cross section is:

$$\sum_{vol} \sigma_i = \frac{\pi^5}{\lambda^4} |K|^2 \sum_{vol} D_i^6 \qquad (m)^2, \tag{2}$$

assuming no polarization mismatch in electromagnetic scattering.

In general, the scattering cross section per unit volume is expressed (Crane, 1973; also 1974) for radar scatter as:

$$\beta = \frac{\pi^5}{\lambda^4} |K|^2 m Z \qquad (m^2/m^3) \tag{3}$$

where $m$ = polarization mismatch factor; and

$Z$ = radar reflectivity factor proportional to the sixth power of particle diameters $\{Z = \frac{1}{V} \sum_{vol} D_i^6\}$.

Usually, the radar reflectivity is expressed as the effective radar reflectivity for rain, $Z_e$, conventionally in units of $mm^6/m^3$ where $Z_e$ is defined as:

$$Z_e \equiv \frac{\lambda^4 \beta}{\pi^5 |K|^2 m} \cdot 10^{18} \qquad (mm^6/m^3) \tag{4}$$

with $|K|^2 \cong 0.93$, ($\varepsilon \sim 81$ for water).

The elemental volume, V, illuminated by a uniform beam and a rectangular pulse in a single radar resolution cell is:

$$V = \pi (R \frac{\Theta}{2}) (R \frac{\phi}{2}) c \frac{\tau}{2} \tag{5}$$

where R = slant range to scattering volume;

$\Theta, \phi$ = radar angular beamwidths;

$\tau$ = pulse width; and

c = velocity of light.

The radar equation for backscattered received power in a resolution cell, assuming uniform $\beta$ over the volumetric element is:

$$P_r = \left( \frac{P_t G^2 \lambda^2}{(4\pi)^3 R^4 L} \right) \cdot \beta \cdot V \tag{6}$$

where $P_t$ = transmitted power delivered to antenna;

G = antenna gain; and

L = total system and propagation losses (two-way), (L > 1).

A more accurate representation of the actual scattering volume is obtained by approximating the antenna pattern as Gaussian shaped in the elevation and orthogonal angle planes (Probert-Jones, 1962), and the time-domain response as a Gaussian shaped pulse. The resulting representation for the volume element of scattering with a single resolution cell is given by:

$$V' = \frac{\pi}{4} R^2 \left( \frac{\Theta\phi}{2 \ln 2} \right) \frac{c\tau}{2} \tag{7}$$

where $\Theta, \phi$ = ½ power beamwidths of antenna (one-way);

$c\tau/2 = D_o \sqrt{\pi/4 \ln 2} = 1.064\ D_o$, (see eqn. (13));

$D_o$ = ½ power range resolution = $c\tau_o/2$; and

$\tau_o$ = ½ power pulse width (compressed).

The average power per resolution cell may be expressed by combining (4), (6) and (7) as:

$$\overline{P}_r = \left(\frac{P_t G^2 \lambda^2}{(4\pi)^3 R^4 L}\right)\left(\frac{\pi^5}{\lambda^4} |K|^2 \, m \, Z_e \cdot 10^{-18}\right)\left(\frac{\pi}{8 \ln 2} R^2 \Theta \phi D_o \sqrt{\frac{\pi}{4 \ln 2}}\right) \quad (8)$$

The scattered power in terms of radar cross section, $\sigma$, from an equivalent point scatterer at the same position as the elemental volume is:

$$P_R = \left(\frac{P_t G^2 \lambda^2}{(4\pi)^3 R^4 L}\right) \sigma \qquad \text{(watts)} \qquad (9)$$

where $\sigma$ = radar cross section ($m^2$).

Equating (8) and (9) permits the equivalent radar cross section of the scattering cell, $\sigma$, to be expressed in terms of effective radar reflectivity, $Z_e$:

$$\sigma = \frac{\pi^6 |K|^2 m \, Z_e \cdot 10^{-18} R^2 \Theta \phi \, D_o \sqrt{\frac{\pi}{4 \ln 2}}}{\lambda^4 \, 8 \ln 2} \qquad (10)$$

2.2 Backscatter Reflectivity for General Hydrometeors

Given that the radar cross section, $\sigma$, is a measurable quantity derived from the calibrated received power output of the radar (the other terms and radar constants of (9) are measured or known), the effective radar reflectivity from a scattering cell may be obtained by solving equation (10) for $Z_e$:

$$Z_e = \frac{\sigma}{R^2} \left(\frac{10^{18} \lambda^4 \, 8 \ln 2}{\pi^6 m |K'|^2 \Theta \phi \, D_o \sqrt{\frac{\pi}{4 \ln 2}}}\right) \cdot \frac{1}{F} \qquad (mm^6/m^3) \qquad (11)$$

where general hydrometeor scatter is relatable to the equivalent for water droplets:

$|K'| = |\varepsilon - 1/\varepsilon + 2| \cdot 1/\rho$;

$\varepsilon$ = dielectric constant for the type of hydrometeor producing effective scatter; and

$\rho$ = ratio of density of the hydrometeor to the density of water.

Equation (11) may alternatively be expressed as:

$$Z_e = \frac{\sigma}{R^2} \frac{C}{F}$$

or $dBZ_e = 10 \log Z_e = \sigma(\text{dBSM}) - 20 \log R + 10 \log(C/F)$ (12)

where C = calibration constant

$$= \left[\frac{10^{18} \cdot 8 \ln 2}{\pi^6 m\sqrt{\frac{\pi}{4 \ln 2}}}\right] \frac{\lambda^4}{|K'|^2 \Theta\phi D_o}$$

$$= 5.42 \times 10^{15} \frac{\lambda^4}{|K'|^2 \Theta\phi D_o}, \quad m = 1.0$$

{R is expressed in meters};

$\sigma$ = radar cross section expressed in decibels relative to a square meter (dBSM); and

F = statistical processing correction factor which depends on signal processing algorithms in use with radar data.

When backscatter is from hydrometeors other than rain from this formulation, it is necessary to use the appropriate value of K' for the type of scatter involved. In the MOIST program processing the height of the scattering volume is obtained from refraction corrected radar parameters in real time and used as a criterion on which to base the use of a K' for ice versus a K' for water. The height used in the program (selectable) is that of the melting layer (~ 0°C isotherm height) and is typically 4.6 km for Kwajalein. This altitude corresponds to the lower edge of the radar "bright-band" below which melting takes place.

## 3. CALIBRATION OF ALCOR AND TRADEX RADARS

The ALCOR (C-band) and TRADEX (S-band) radars operate in a narrow band pulse compression mode (CHIRP) for hydrometeor scatter measurements. The compressed output pulse (matched filter response) may be modeled as approximately Gaussian shaped. This assumption is consistent with quoted 3- and 6-dB pulse widths and the shape of time response plots obtained during calibration runs. For the radars, the sampling volume is defined by the antenna beamwidth and the response of the pulse compression circuits. In angle, the volume definition is given by Probert-Jones (1962) as indicated in the previous section. In range, the volume is defined by the integral over the time response:

$$\frac{c\tau}{2} = \int_{-\infty}^{\infty} e^{-4\ \ln 2 (\chi/D_o)^2} d\chi = D_o\sqrt{\frac{\pi}{4\ \ln 2}} = 1.064\ D_o \qquad (13)$$

where $D_o = \frac{c\tau_o}{2}$ = pulse resolution width ($\tau_o$ = 3 dB pulse width).

From the derived expressions (11) and (12) the effective radar reflectivity ($mm^6/m^3$) may be obtained from the measured radar scattering cross section, range to the scattering volume, calibration constant C, and processing factor F. The radar parameters and calibration constants are given in Table 2 for the current best estimate values for the two KREMS radars.

### 3.1 Signal Processing Corrections

The processing correction factor, F, is used to adjust for the biases introduced in the average value of the randomly varying signal received from an ensemble of point scatterers within the scattering volume. The processing correction factor depends upon the particular digital signal processing scheme employed in the data reduction chain to obtain the equivalent scattered cross section used in equation (12). The correction factor accounts for biases due to: digital quantization (sometimes referred to as truncation error); detection cell selection algorithm biases; and biases associated with averaging the logarithm of the amplitude rather than the value of the received power. In contrast

TABLE 2

RADAR PARAMETERS* FOR VOLUMETRIC SCATTER FROM HYDROMETEORS

| Parameter | ALCOR | TRADEX | Units |
|---|---|---|---|
| $\lambda$ | 0.05292 | 0.1016 | (m) |
| m | 1.0 | 1.0 | - |
| $\Theta = \phi$ | $5.3 \times 10^{-3}$ | $5.0 \times 10^{-3}$ | (rad.) |
| $D_o$ | 37.5 m | 10.4 | (m) |
| $\|K'\|^2$ ice | 0.209 | 0.209 | - |
| $\|K'\|^2$ water | 0.933 | 0.934 | - |
| C ice | 82.9 (142.9) | 100.3 (160.3) | (dB) |
| C water | 76.4 (136.4) | 93.8 (153.8) | (dB) |

Values in parentheses are for range expressed in meters, otherwise R is in km

to most weather radars, the KREMS radars are calibrated effectively using the center of the quantization unit. A quantization correction, therefore, is not required since no bias should be introduced. The detection cell selection algorithms and received pulse averaging schemes introduce significant amplitude biases which may be corrected.

The two statistical sources of bias produced by the processing scheme used with the KREMS radars are those introduced by averaging the logarithm of the received signal (both radars) and the "greatest-of-four" (consecutive range samples) algorithm used in the real-time MOIST** processing of the ALCOR data. The probability density function of the average of a number of independent samples of received power in a resolution cell approaches a Gaussian function for a large sample size (exceeding 10; see Smith, 1964). For the case in which the receiver has a logarithmic amplitude response (as for the KREMS radars), the average

*Note that the parameters in Table 2 have been revised from those published by Lewis (1978), mostly due to improved radar beamwidth and range resolution information.

**MOIST is a software program used at KREMS for real-time estimation of liquid water content using either ALCOR or TRADEX radar data output.

of the log power ($\overline{10 \log P_R}$) is obtained. The desired quantity $10 \log \overline{P}_R$ (logarithm of the average power) is obtainable with a correction term:

$$10 \log \overline{P}_R = \overline{10 \log P_R} + 2.51 \text{ dB} \tag{14}$$

The bias correction term in F due to averaging log power is therefore 2.51 dB.

For ALCOR, with the data obtained in real-time and processed through the MOIST program, the greatest-of-four consecutive range samples are selected prior to averaging for post detection processing. The samples are not independent since the half-power range resolution is 37.5 meters but samples are taken every 15 meters. The correction for the effect of processing using the greatest-of-four detection algorithm can be estimated either through simulation (Smith, 1964) or by direct measurement. The results in Table 3 were obtained by direct measurement by employing the MOIST processing scheme off-line using data obtained from an ALCOR data tape. A summary of the combined processing factor F for data processed with the radars is included in Table 3 together with the corrected calibration constant, C/F.

3.2 Radar Cross Section Calibration

The radar parameters contained in parentheses in equation (9) must either be measured or deduced to obtain a correct estimate for radar cross section, $\sigma$, given the measured value of received power. The KREMS radars are calibrated by tracking a calibration sphere of known radar cross section. The constants with the exception of transmitted power and range are deduced from the radar tracks of several spheres. The resulting expression for an unknown scattering cross section is:

$$\sigma = P_R \left(\frac{R^4}{P_T}\right) K_{RCS} \qquad (m^2) \tag{15}$$

where $R$ = measured range to scatterer (meters);

$K_{RCS}$ = constant obtained from external sphere target RCS calibration

$= \frac{(4\pi)^3 L}{G^2 \lambda^2}$, {$\sim$ -90 dB for ALCOR}, ($m^{-2}$);

$P_R$ = measured received power (watts)

TABLE 3

CORRECTION FACTOR, F, AND CORRECTED CALIBRATION CONSTANT C/F USED (EQUATION 12) IN CONVERTING MEASURED RADAR CROSS SECTION, $\sigma$, INTO EFFECTIVE RADAR REFLECTIVITY, $Z_e$

| Correction | ALCOR MOIST Processing | ALCOR Data Tape | TRADEX MOIST Processing |
|---|---|---|---|
| Quantization | 0 dB | 0 dB | 0 dB |
| Average of Log $P_R$ | -2.5 dB | -2.5 dB | -2.5 dB |
| Greatest-of-Four Algorithm (direct measurement-ALCOR) | +3.3 dB | - | - |
| Total F (dB) | +0.8 | -2.5 | -2.5 |
| C/F ice (dB) | 82.1 (142.1) | 85.4 (145.4) | 102.8 (162.8) |
| C/F water (dB) | 75.6 (135.6) | 78.9 (138.9) | 96.3 (156.3) |

Note: Values in parentheses are with range, R, expressed in meters instead of kilometers

$$= P_{OUT} + A \qquad (dB);$$

$P_{OUT}$ = power received after attenuation (watts);

$A$ = total attenuation in receiving system (dB);

$L$ = total two-way system loss including transmission lines and propagation ($L > 1$);

$G$ = on-axis radar antenna transmit and receive gain factor; and

$\lambda$ = radar operating wavelength (meters).

Expressed in decibels, equation (15) becomes:

$$\sigma_{(dBSM)} = P_{OUT} + A - P_{T_{(dBW)}} + 40 \log R + K_{RCS} \tag{16}$$

where $P_{OUT}$ = Table A/D reference (dBW) + Table A/D difference (dB).

Figure 1 shows a simplified block diagram of the ALCOR radar, for example (narrow band waveform configuration), used in most weather radar applications. The receiver chain is calibrated by signal injection preceding the logarithmic detector. The output is A/D converted prior to digital recording. The characteristic curve, A/D output versus input level, may be obtained by either a curve-fitting or a point-by-point calibration at each quantization level. The actual procedure with ALCOR is to produce a calibration table (dB referenced to the highest A/D level, 127) for each A/D count (level) over the response dynamic range. The output power for equation (16) is therefore obtained as the table A/D difference value (dB) added to the table A/D reference value (dBW) obtained for the reference count level. This look-up table method results in a calibration characteristic for the log detector and A/D chain which has no net quantization bias but varies about the mean fitted curve by a residual amount typically less than one quantization unit in magnitude (0.55 dB for ALCOR, 1.11 dB for TRADEX). There is, however, a maximum uncertainty associated with this procedure of the order of ½ of the quantization value ($\sim$ 0.25 and $\sim$ 0.5 dB, respectively), depending on the instantaneous signal level within the dynamic range. Assuming some signal fluctuation throughout the period of averaging, the uncertainty associated with this measurement procedure will be reduced below

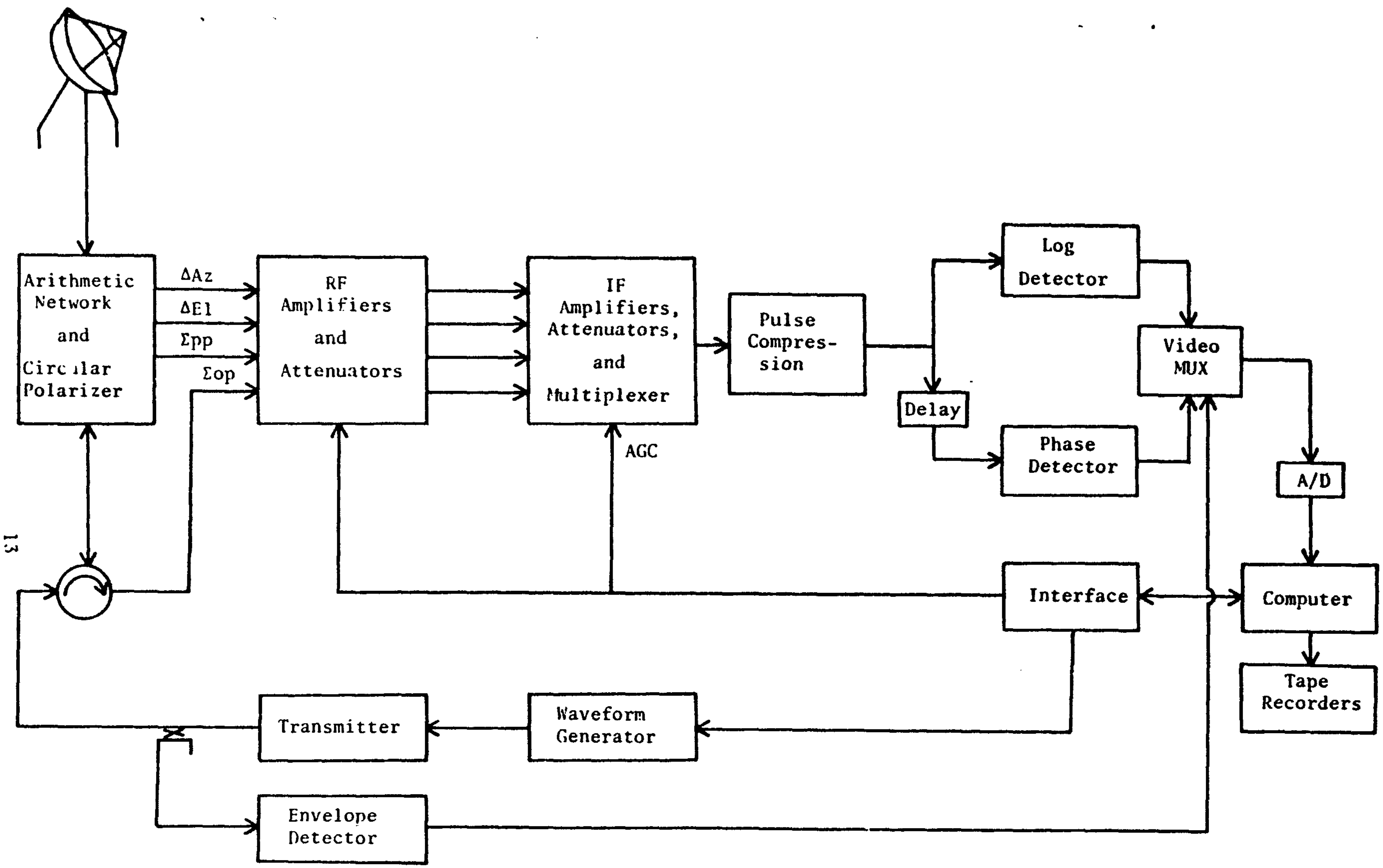


Figure 1    Simplified block diagram of the ALCOR radar used for weather radar applications

that expected on a single pulse basis. The uncertainty (one standard deviation) is equal to the magnitude of the quantization step divided by the square root of 12 times the number of independent samples.

The other terms remaining in equation (16) may also have uncertainties associated with their measurement. Some of these are negligible such as those produced by the attenuator calibration (less than ±0.05 dB error) and that of range R estimation (less than ±0.1 dB). The transmitted power, $P_T$, is monitored and factored into the calibration procedure by the radar real-time program. Though the transmitted power level may vary slowly, or on a mission-by-mission basis, the calibration procedure removes all but a random component which is estimated to be less than ±0.1 dB. The term which has the largest uncertainty is the calibration constant $K_{RCS}$ usually obtained from sphere calibrations preceding or following a mission run. The uncertainty associated with a sphere of "known" radar cross section (RCS) depends on the size of the sphere relative to the radar wavelength. For scattering from a sphere within the optic regime ($ka > 10$, $k = 2\pi/\lambda$, $a$ = sphere radius) the RCS uncertainty is less than ±0.5 dB assuming a perfectly spherical shape. The 20-inch diameter spheres, flown for radar calibration before and after missions at Kwajalein, are clearly within the optical criterion cited, at the radar wavelengths ($ka \sim 30$ for ALCOR C-band, $ka \sim 16$ for TRADEX S-band).

Other factors may enter into the procedure of calibration beyond the uncertainty of knowing the precise sphere RCS. Since $K_{RCS}$ contains propagation losses as well as system parameters there may be differences between those encountered during sphere calibration and those during actual operation for hydrometeor scatter. Some of these are: different path attenuations (due to absorption or hydrometeor attenuation) associated with the different atmospheric paths; differences associated with tropospheric refraction effects; variations in radome attenuation due to rain at ALCOR; uncertainties associated with target positioning within the radar beams; and gradual changes in system gains, losses or matched filter response from the time of calibration to the time of measurements. Generally, the differences are randomly occurring events, the magnitude of which can only be estimated through many observations. Typically, the changes in calibration constant, $K_{RCS}$, an indication of some of these effects occurring, are not more than ±1-to-2 dB from one sphere calibration to the next and this principally charged to variation in channel gain. During an operational period, the radar system itself is considered stable to about ±0.5 dB. The uncertainty, therefore, associated with $K_{RCS}$ depends on the proximity in time and space of the scatter measurement to the sphere calibration and upon operator care in system set-up. It is estimated that errors in determining $K_{RCS}$ are ±0.6 dB (±1.8 dB at $3\sigma$)including the sphere RCS uncertainty when conditions are nominal, i.e. no rain occurrs at the radars and sphere calibrations are made within a few hours of the measurement run. This estimate is based upon an analysis of sphere calibration results for TRADEX during a four-month period in 1977 which resulted in an RMS error in sphere calibrations to be within 1 dB (see also Crane, 1978). The errors for a particular mission are less than the variability for a number of widely spaced sphere calibrations. Errors associated with other propagation effect differences, e.g., gaseous attenuation, hydrometeor attenuation and system loss changes (from calibration to mission), are estimated at 0.5 dB for ALCOR and 0.3 dB for TRADEX. The uncertainties are summarized in Table 1.

## 4. HYDROMETEOR SCATTER DATA AND INTERPRETATION

Radar measurements of hydrometeor scatter at Kwajalein are collected for diagnostic as well as operational purposes. When diagnostic measurements are taken, an instrumented aircraft is flown to sample the precipitation and make direct measurements. The radars are slaved to continuously track a scattering volume ahead of the aircraft path such that data may be correlated between the two sets of measurements. An arbitrary sample of data from a correlation run is examined next, simply to illustrate the type of data collected and to provide a basis for discussing the interpretation of rain scatter data in particular.

### 4.1 Short Sample of Rain Scatter Data

An example of rain scatter measurements is shown in Figure 2 for one of several correlation runs (taken near Roi-Namur Island) on June 26, 1979. This short selected sample occurred for a data collection pass through a light rain shower region which was relatively inhomogeneous. The reflectivity data are from MOIST data processing at a rate of one averaged value per second. Both ALCOR and TRADEX radar data are shown on the figure for comparison. Typically, the effective radar reflectivity in decibels, dBZ (varying in this case from -20 to +30 dBZ), correlates well between measurements taken by the two radars with similar scattering volume resolution (as noted in Table 2). Shown also in the figure is the ratio of principal (PP) to opposite (OP) received backscatter polarization. The principal polarization for a circularly polarized radar is defined as left-circular when right-circular polarized waves are transmitted (opposite, is right-circular).

### 4.2 Use of Cross Polarization as an Editing Criterion

When operating under conditions where rain is the supposed cause of hydrometeor scatter, one can use the radar cross polarized channel as an indication or gage of the nature of the radar backscatter as rain rather than another form of hydrometeor. The scattered components of the electromagnetic field received by the radar antenna as cross polarized, will increase (in the case of backscatter) as the scatterers depart from

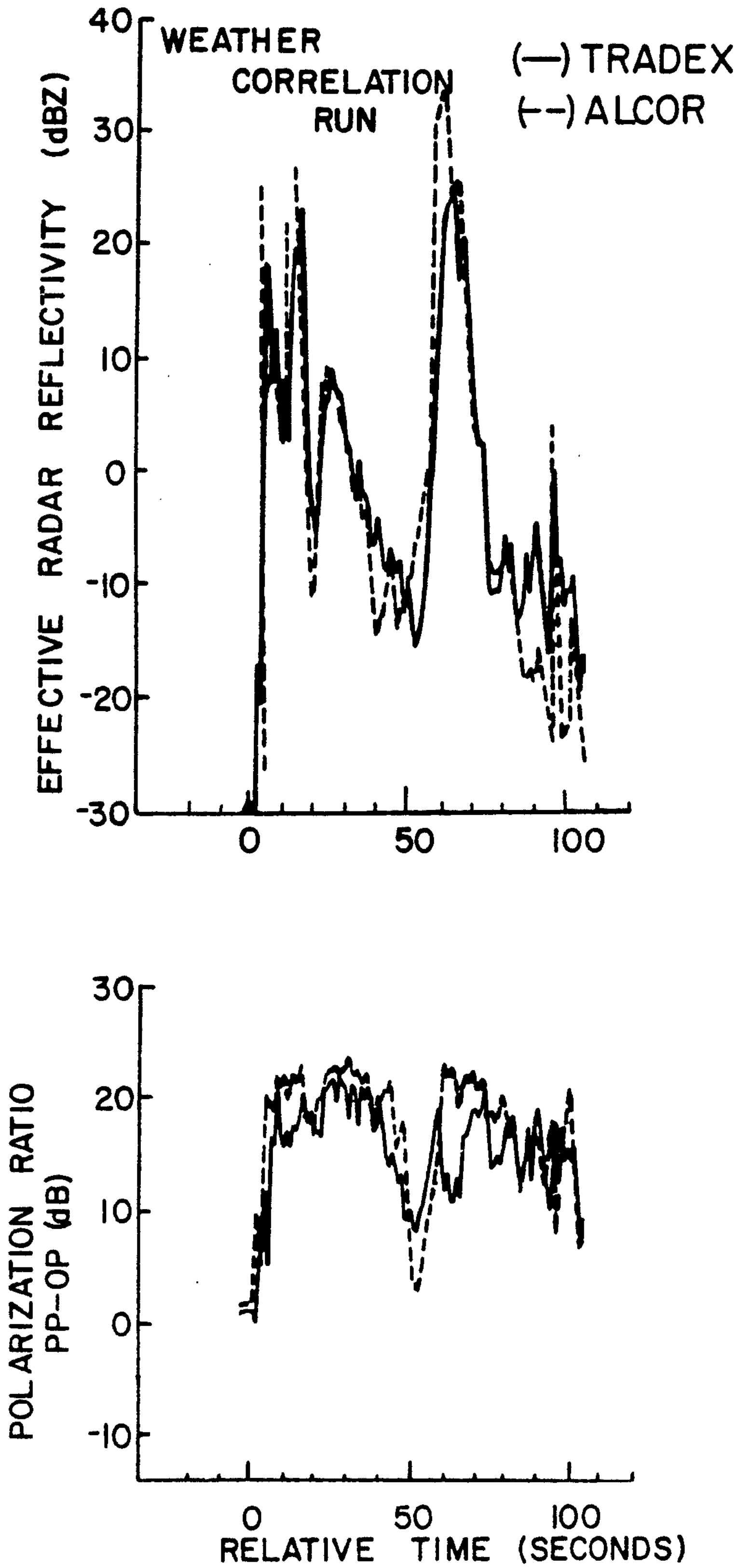


Figure 2 Example of effective radar reflectivity measurement, dBZ, obtained for rain on ALCOR and TRADEX radars (variable conditions near island of Roi-Namur)

having a spherical shape. Depolarization, or a rise in the cross polarized channel signal power, is an indication of the non-symmetrical nature of the scatterers such as would be expected from prolate or oblate spheroids when viewed at an arbitrary angle. Spherical rain drops, in contrast, should backscatter no field component with the polarity opposite to that defined as principal on the axis of the radar beam. The ratio of principal to orthogonal PP/OP polarized returns does not go to infinity however due to channel isolation limits of the antenna system (approximately 26 to 28 dB).

The oblateness of raindrops is a function of size and hence rain rate. Since these characteristics are measurable and known as a function of rain temperature, one can derive a relationship for the polarization ratio terms of rain rate and total scattered reflectivity. The ratio of power received in the principal to the power received in the opposite channel for non-canted raindrops at a radar frequency, F, is therefore:

$$PP/OP = \left|\frac{P-1}{P+1}\right|^2 \tag{17}$$

where $P = [Z_V/Z_H]^{\frac{1}{2}}$;

$Z_V$ = reflectivity for vertical linear transmitted and received polarization at frequency F; and

$Z_H$ = reflectivity for horizontal linear transmitted and received polarization at frequency F.

Expressed in decibels, (17) is:

$$PP - OP\ (dB) = 20 \log_{10} \left|\frac{P-1}{P+1}\right| \tag{18}$$

Once again, this result is only true in the ideal sense for oblate spheroidal raindrops, with a vertical orientation of the axis of symmetry, scattering on-axis to the radar beam, with a zero depth of penetration into the scattering volume, and received on a perfectly polarization balanced radar antenna system at very high signal to noise ratios. With a non-ideal real radar system, some allowance must be made for degradation due to each of these sources of departure. It is still of utility, however, to derive a rule of thumb for judging the quality of radar rain backscatter by establishing an editing criterion albeit somewhat arbitrary (3 dB or more departure from ideal, as a function of dBZ level), without a careful investigation into each potential source of polarization degradation. As a result, the included table of minimum editing rules, Table 4, may be considered usable as an estimate of the necessary, but not sufficient, conditions to select the total backscattered dBZ levels as truly rain scatter in nature. The table is for rain at 10°C and at a radar frequency of 4 GHz (approximately mid range between the ALCOR and TRADEX radar frequencies). Quite obviously, further study into this type of classification could perhaps yield a refinement of the criterion and a similar means of classification for other habits of hydrometeor activity as well as for rain.

TABLE 4

EDITING RULES FOR ASSISTING IN THE SELECTION OF USABLE RADAR BACKSCATTER DATA FROM RAIN

| Range of dBZ | Minimum Rule* | Ideal (Theory) |
|---|---|---|
| If dBZ < 0, | then PP-OP > 20 dB | off scale |
| 0 ≤ dBZ < 10, | then PP-OP > 19 dB | - |
| 10 ≤ dBZ < 20, | then PP-OP > 18 dB | 30 |
| 20 ≤ dBZ < 30, | then PP-OP > 17 dB | 25 |
| 30 ≤ dBZ < 40, | then PP-OP > 15 dB | 20 |
| 40 ≤ dBZ < 50, | then PP-OP > 13 dB | 17 |
| 50 ≤ dBZ < 60, | then PP-OP > 12 dB | 15 |
| 60 ≤ dBZ, | then PP-OP > 11 dB | 14 |

*Somewhat arbitrary at lower dBZ values due to lack of knowledge of noise statistics influencing the PP/OP ratio

## 5. SUMMARY AND CONCLUSIONS

The ALCOR (C-band) and TRADEX (S-band) radars at Kwajalein are well-calibrated instrumentation radars which serve among many other roles to provide measurements of the environmental conditions of hydrometeor activity within the reentry corridor of the Kwajalein Missile Range (KMR). This report defines the essential radar parameters, assesses significant sources of error in these parameters and documents the most recent best estimate of the appropriate radar constants to use in data processing. A discussion of the calibration procedures is also given with a recognition of the ultimate importance of sphere calibrations in close space and time proximity to the hydrometeor scatter measurements of interest for minimizing the calibration uncertainties. The overall RMS ($1\sigma$) uncertainties associated with the radar measurement are estimated at 1.0 dB each for ALCOR and TRADEX as summarized in Table 1. This assumes that the bias terms associated with signal processing are appropriately accounted for by the use of the best estimate correction factor given in Table 3 and that the radar parameters given in Table 2 do not change. Implicit in this analysis is the assumption that a zero dB polarization mis-match loss occurs for hydrometeor scatter and that excess losses, such as radome attenuation changes due to rain or condensation of moisture on the ALCOR radome, do not occur during the measurements.

An initial attempt to classify rain scatter on the basis of principal to opposite polarization ratio is presented. This tool, useful for data editing and interpretation, suggests that further means of classifying the hydrometeor backscatter may be intrinsically available in the different radar polarizations and worthwhile for further investigation at Kwajalein.

## 6. REFERENCES


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